

Electromagnetic Absorbers Based on Metamaterial and Plasmonic Devices

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Abstract—The objective of this paper is to focus on reviewing the recent advances in research on metamaterial and plasmonic absorbers. Metamaterials provide excellent flexibility, robustness and tunability to efficiently control and manipulate the absorption of electromagnetic energy in unprecedented ways compared to natural absorbing materials. They are mainly fabricated by using ultrathin metallic parts and their operation is based on physical mechanisms that are different from those of the conventional microwave absorbers which are usually quite bulky, since they typically utilize lossy magneto-dielectric materials. The unique metallic nature of metamaterials and their ultrathin dimensions can lead to novel functionalities when combined with their highly absorbing properties, such as manipulation of absorption of electromagnetic radiation and the reciprocal effect of thermal emission of electromagnetic waves, which occurs when they are heated. All the presented electromagnetic absorber designs can be scaled up or down to both low and high frequencies, to operate at microwaves, THz, infrared and optics. This can be achieved by just changing the dimensions and properties of each device depending on the particular application. It will be shown that these devices provide an ideal platform for taming and controlling the absorption by metallic structures in unique ways. The use of absorbers based on metamaterial and plasmonic structures can lead to the design of new bolometers, efficient energy harvesting devices and novel thermo-photovoltaic structures.

Index Terms—Metamaterials, Plasmonics, Absorption, Solar cells, Bolometers, Photovoltaic technology.

I. INTRODUCTION

Metamaterials are artificially synthesized structures with novel functionalities that are impossible to realize by using natural materials. Recently, exotic electromagnetic effects have been achieved with the usage of metamaterials, such as invisible cloaks [1]-[3] and negative refractive index media [4]-[6]. These structures typically comprise of periodically-arranged sub-wavelength inclusions that are highly conductive metals printed on dielectric substrates and they can be usually analyzed by using an effective medium theory [7]-[8]. In infrared (IR) and optical frequencies, these devices may efficiently control and enhance light-matter interactions at deeply sub-wavelength scales [9], beyond the limits usually associated with diffraction. An electromagnetic wave may induce highly localized surface waves on metallic interfaces in this high frequency regime. The obtained resonant coherent

oscillations of the conduction-band electrons at these interfaces are called ‘surface plasmons’; and the physical phenomenon associated with them has recently spawned the field of plasmonics [10]-[11]. Different applications are envisioned that are based on extreme confinement of light and on utilizing the large electromagnetic fields that are induced by resonant plasmonic effects, such as enhanced nonlinear optical processes [12]-[15]. Furthermore, novel electromagnetic absorber designs can be achieved based on the destructive interference and strong dissipation of the strongly confined and extremely coupled electromagnetic radiation, which can lead to new photovoltaic designs with very high levels of efficiency [16]-[17].

Our objective in this work is to review the novel absorbing characteristics of different metamaterial and plasmonic devices. We will also provide a glimpse of their thermal emission properties, which may also lead to novel energy harvesting devices. Recently, there have been increased theoretical and experimental efforts that serve to demonstrate how plasmonic metallic nanoparticle arrays or metamaterial resonators and gratings are helpful in boosting the overall absorption in solar panels and semiconductor substrates [16]-[17]. However, most of these techniques are inherently sensitive to the frequency of operation and they are typically narrowband. They are primarily based on the introduction of highly resonant electric and magnetic elements over lossy dielectric and metallic substrates [18]-[23]. Efficient coupling of both electric and magnetic fields inside their substrate leads to enhanced absorption at their resonance frequency. Here, we will focus our attention on a particular narrowband absorber design, which operates at IR and optical frequencies and can be built by colloiddally synthesized plasmonic nanoantennas [24]. The absorber is composed of film-coupled metallic nanocubes placed in an array formation over a metallic substrate. These resonant optical elements are equivalent to the well-established patch antennas at microwave frequencies. The presented narrowband absorber design works for both polarizations and for all angles of incidence of the impinging radiation.

Recently, considerable effort has been devoted toward realizing broadband absorption operation either by using tapered metallic geometries or by combining multiple resonances [25]-[26]. These solutions still exhibit bandwidth limitations, since they fundamentally rely on resonant processes. In this work, we will present an alternative and inherently broadband and omni-directional absorber design

[27], which is based on the recently introduced concept of Brewster energy tunneling through plasmonic metallic gratings [28]-[30]. The interface between free-space, or dielectric materials, and plasmonic gratings may be completely impedance matched over an ultra-wide frequency range. However, this may only happen at a specific angle of incidence, i.e., the Brewster angle, and only for transverse-magnetic (TM) polarized incident waves. This effect is inherently broadband and can lead to absorber designs with ultra-broadband operation, spanning the entire optical frequency range going down to IR and even low THz.

We will also present alternative efficient and broadband or narrowband absorbing and energy concentrating devices, which can be designed based on the recently introduced concept of transformation electromagnetics [2]. They can focus and absorb the impinging electromagnetic waves using a gradually matched material profile. Different designs of these devices will be presented, such as lossy electromagnetic cloaks [31], electric field concentrators [32] and optical ‘black holes’ [33]-[34]. These exotic structures demonstrate perfect and omni-directional absorption or concentration of the impinging electromagnetic radiation at different frequency ranges, such as microwaves and optics. As a general note, we would like to mention that the geometries of most of the proposed structures can be scaled down or up to operate in different frequencies with minor modifications and without losing their perfect absorption functionalities.

Finally, in view of the reciprocity principle, the proposed absorber designs may also operate as narrowband or broadband selective or omni-directional black-body radiators [27], [35]-[37], when their metallic parts are heated up to an appropriate temperature. For example, the Brewster metasurface absorber design is capable of emitting thermal radiation similar to a black-body over a very broad range of frequencies, but with more angular selectivity, which may ensure directive radiation towards the desired location [27]. These properties are advantageous towards the efficient focusing and concentration of solar radiation in the next-generation multi-junction solar cells and they can lead to novel thermo-photovoltaic devices. In general, all the proposed metamaterial and plasmonic devices demonstrate groundbreaking potentials towards the construction of the future “environmentally-friendly” energy sources. They may provide a revolutionary path towards alternative and clean energy harvesting.

The paper is organized as follows. In Section II the theoretical calculations to compute the electromagnetic absorption are briefly reviewed. Section III presents different designs of metamaterial and plasmonic absorbers, which may exhibit a narrowband or broadband operation. The presented designs can be built with sub-wavelength metallic resonators, Brewster angle metasurfaces and transformation electromagnetic concepts. Finally, some concluding remarks are provided in Section IV.

II. ABSORPTION OF ELECTROMAGNETIC WAVES

Naturally occurring materials, as well as the artificially synthesized metamaterials, can be defined by means of

complex electromagnetic parameters, such as the frequency dependent permittivity $\varepsilon(\omega) = \varepsilon'(\omega) + j\varepsilon''(\omega)$ and permeability $\mu = \mu'(\omega) + j\mu''(\omega)$. Until recently, metamaterial research has been mainly concentrated on the real parts (ε', μ') of these material parameters in order to design exotic devices, such as negative-index lenses and cloaking structures [1]-[6]. However, the imaginary parts (ε'', μ'') of the material parameters, which characterize the losses of the obtained bulk medium, may also have interesting potential applications, such as the design of more efficient thermal imagers and novel absorbing structures. In this review, the advantages of the overlooked lossy properties of metamaterials will be presented, which are conventionally regarded as a major drawback in the design of artificial structures.

To achieve the design of a perfect absorbing body it is necessary to maximize its electromagnetic absorption, which is given by the relationship: $A = 1 - R - T$, where the reflectance is $R = |S_{11}|^2$ and the transmittance is $T = |S_{21}|^2$. The reflection (S_{11}) and transmission (S_{21}) coefficients can be computed with numerical simulations or measured with an experimental set-up; usually with a vector network analyzer (VNA) in microwave and THz frequencies or optical detectors and spectrometers in IR and optical frequencies.

Normally, it is relatively straightforward to make the transmittance of an object equal to zero. A device can be simply made opaque in electromagnetic radiation by just being terminated with a perfect electric conductor (PEC) or a metallic screen with thickness larger than its skin depth. Both of these terminations act as perfect reflectors to the impinging electromagnetic radiation. The fields cannot penetrate through these screens and, as a result, the observed transmittance becomes zero ($T = 0$).

However, it is much more challenging to make the reflectance of the proposed device approximately equal to zero. Impedance matching techniques with the surrounding space need to be considered in this case. These usually require narrowband resonant metamaterials to be achieved. The real and imaginary part of the electric permittivity and magnetic permeability can be manipulated in such way as to match the impedance of the metamaterial device to the impedance of the surrounding space, which is usually assumed to be free space. In this case, the following relation needs to be satisfied:

$$Z = \sqrt{\frac{\mu' + j\mu''}{\varepsilon' + j\varepsilon''}} = \sqrt{\frac{\mu_0}{\varepsilon_0}}, \quad (1)$$

where ε_0, μ_0 are the permittivity and permeability of free space. Usually, the perfect impedance matching condition [Eq.(1)] can be accomplished only at a narrow frequency range, ideally only at one frequency point, where perfect electric and magnetic coupling can be achieved by electric and magnetic metamaterial resonating inclusions.

Alternatively, it can be achieved by thick magneto-dielectric layered materials. In the next section, we will demonstrate an interesting plasmonic example, where Eq. (1) can be satisfied over a broader frequency range.

III. METAMATERIAL AND PLASMONIC ABSORBERS

A. Narrowband Absorbers

In this section we present different metallic metamaterial and plasmonic absorbers based on the plasmonic structure depicted in Fig. 1(a). It can be characterized as a metasurface, i.e. a two-dimensional (2D) metamaterial, due to its sub-wavelength thickness perpendicular to the direction of wave propagation. It is composed of metallic cubes made of silver (Ag) periodically arranged over a dielectric spacer layer and a silver film. It constitutes a perfect narrowband absorber [24], because the fields are perfectly coupled and trapped inside the nanogaps created between the cubes and the film at the resonance frequency, as it will be numerically demonstrated later. In this case, a magnetic and electric wall is formed, leading to destructive interference in the reflected waves and, as a result, very low radiation is reflected from the metasurface [24]. The silver film makes the structure opaque to impinging radiation with a transmission coefficient almost equal to zero. Therefore, almost perfect absorption is expected to be obtained at and nearby the resonance frequency of this plasmonic metasurface. In addition, it is rather straightforward to experimentally realize this plasmonic structure with colloidal self-assembly processes [24], [38], which makes its practical potential even more significant. Note that the reflectance and equivalent absorption of metasurfaces can be efficiently controlled by just changing the geometry and the material used as the spacer layer, leading to tunable operation [24].

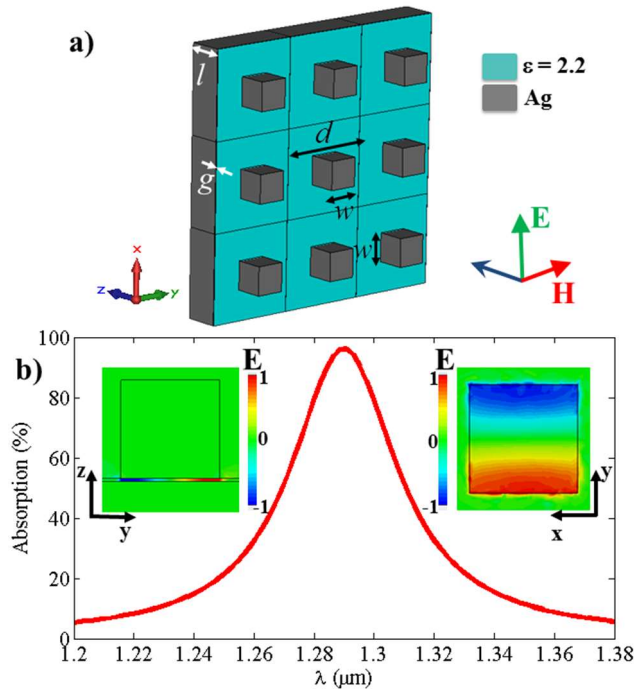


Fig. 1. (a) Film-coupled plasmonic nanoantenna array with a dielectric material loaded at the spacer layer. (b) Percentage of absorption versus the wavelength of the impinging radiation. The normalized electric field distributions at the resonant absorption peak are shown in two cross-sections in the inset. Standing waves are formed inside the gap between the metallic cube and the silver film.

The geometry of the film-coupled plasmonic nanocubes absorber is plotted in Fig. 1(a) and has dimensions $w = 80\text{nm}$, $d = 250\text{nm}$, $g = 2\text{nm}$ and $l = 100\text{nm}$. The cube and the metallic film are made of silver with dielectric properties obtained by experimental data [39]. A dielectric material is loaded at the spacer layer with relative permittivity $\epsilon = 2.2$. The plasmonic structure is simulated with commercial software (CST) based on the finite-integration method. The absorption is plotted in Fig. 1(b) and a pronounced peak of almost perfect absorption is obtained at the resonant wavelength $\lambda = 1.29\mu\text{m}$ of the plasmonic system. The quality factor of this resonance is approximately $Q \approx 60$, which is a typical value for plasmonic resonators. Standing waves are built inside the subwavelength nanocavities formed between the nanocubes and the metallic film. Two cross-sections of the normalized field distributions are depicted in the inset of Fig. 1(b) at the resonant wavelength. It is clear that a first-order Fabry-Perot mode is formed between the nanocube and the metallic film, which leads to trapped fields inside the nanocavities and enhanced absorption at this particular frequency point. Finally, note that the presented structure is an optical analogue of the well-established patch antenna, widely used in microwave frequencies, mainly for mobile communications. It can be easily analysed with microwave engineering techniques [40].

Hence, an array of plasmonic nanoantennas is used to improve the performance of existing infrared and optical absorbers, which may have a number of potential applications in thermal emitters, sensors, spatial light modulators, infrared camouflage, optical communications and thermo-photovoltaics. Highly-efficient optical absorbers can be designed based on this dense array of plasmonic nanoantennas, and they can achieve almost perfect absorption at a relevant narrow frequency range. Additionally, the presented absorbing device is expected to exhibit the same reflection or absorption response when excited with different polarizations and angles of incidence radiation waves, as was previously reported in [24]. Therefore, it constitutes an omni-directional perfect absorber working for different polarizations. When heated, its thermal emission will be very similar to the perfect blackbody emission distribution; however, it will be limited in a narrow frequency range.

Indeed, self-assembled nanoantenna arrays separated from a metallic film by a thin insulating layer can offer strong localization of electromagnetic radiation and may also lead to new types of efficient light-trapping structures used in conjunction with thin-film solar cell devices [41]-[44]. In general, the main operation principle of these devices relies on the excitation of collective plasmonic modes through the nanoantenna array, with the electric field strongly localized

between the adjacent metallic elements. The presented planar array of plasmonic nanoantennas is ultrathin (sub-wavelength thickness) and yields better absorption efficiency compared to conventional, usually thick and bulky, anti-reflecting coatings. These are ideal conditions for designing novel efficient thin-film solar cells. Note that if the array of the nanoantennas is not terminated by a thick metallic film or reflector, it will only absorb half of the impinging radiation due to symmetry limitations. However, in our case, an efficient narrowband absorber design is realized simply by breaking this symmetry, which is conveniently achieved by backing the nanoantenna array with a thick metallic film acting as the substrate.

In addition, rectifying antennas (rectennas), operating at microwave and low THz frequencies, may be loaded with diodes and can be used to directly rectify the impinging radiation and convert it into electricity [45]-[46]. Finally, we would like to note that metamaterial and plasmonic resonators may offer even greater robustness in their absorption response in terms of operating at even higher frequency ranges, such as ultra-violet (UV). For instance, recently, it has been demonstrated that an array of core-shell aluminum-dielectric nanoparticles can realize efficient absorbing devices at UV frequencies [47], which can be used as solar blinds to isolate and absorb the harmful UV radiation from devices used in military applications.

B. Broadband Absorbers

Typically, magnetic and electric resonances are created with different metamaterial resonators leading to impedance matching with the surrounding space and, as a result, perfect absorption of the impinging electromagnetic radiation. However, such techniques are inherently sensitive to the frequency of operation, which severely limit their practical use in energy-harvesting devices, where the entire spectrum of the Sun's radiation needs to be absorbed. The severe limitation of narrowband operation can be overcome by utilizing the concept of the broadband Brewster energy tunneling through metallic gratings [28]-[30], which was recently experimental verified in microwave frequencies [48]. This phenomenon is the analogous of the well-known Brewster transmission effect for dielectric slabs. When applied to metallic gratings, it has the remarkable property of funneling and concentrating the impinging electromagnetic radiation within their sub-wavelength slits. This can result in large concentration of energy within very small volumes, with remarkable differences compared to any other resonant mechanism for energy concentration and focusing, since it does not have specific limitations on bandwidth and can be obtained with a much lower Q factor. This effect can be applied to both one-dimensional (1-D) [28]-[29] and two-dimensional [30] metallic gratings. Input and output interfaces are not needed to establish this tunneling phenomenon, as in the case of conventional Fabry-Perot resonant tunneling, which is usually excited at sub-wavelength grooves or slits of metallic gratings [49]-[50]. It is only based on the perfect impedance matching of the impinging electromagnetic radiation.

The geometry considered for demonstrating the Brewster angle tunnelling concept is shown in Fig. 2. It is composed of a silver metallic screen of thickness $l = 200\text{nm}$, corrugated by slits of width $w = 12\text{nm}$ and period $d = 96\text{nm}$. The slits are loaded with air and the grating is surrounded by free space. The structure is illuminated by a TM electromagnetic wave, obliquely incident at an angle θ_i . The scattering performance of such a periodic structure is modelled using a Transmission-Line (TL) approach, as described in [28]-[29]. The metallic grating will exhibit broadband transmission at the Brewster angle, even when different dielectrics are loaded inside the slits or surround the grating [29]. The dispersion of the silver permittivity is again taken by experimental data [39]. It follows a Drude dispersion model

$$\text{with } \varepsilon = \varepsilon_\infty - \frac{f_p^2}{f^2 - j\gamma f}, \quad \text{where } f_p = 2175\text{THz},$$

$$\gamma = 4.35\text{THz}, \quad \varepsilon_\infty = 5.$$

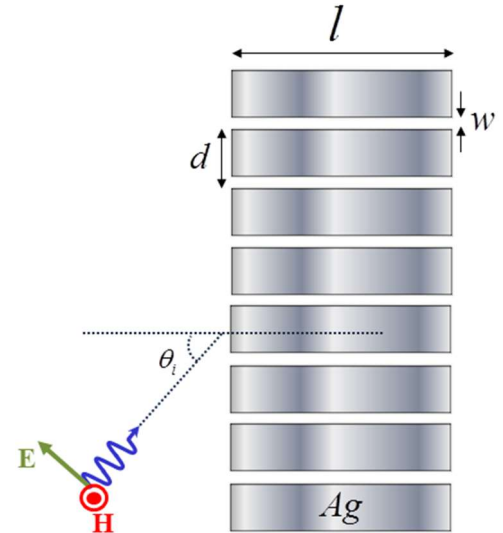


Fig. 2. Schematic of the silver grating illuminated by a TM polarized electromagnetic wave.

In order to achieve perfect impedance matching between the grating and the surrounding free space, the angle of incidence of the impinging radiation needs to be equal to the Brewster angle of incidence. This happens when the following relation is satisfied [28]-[29]:

$$\cos \theta_B = \frac{\beta_s w}{k_0 d}, \quad (2)$$

where $k_0 = \omega / c$ is the free-space wave number, c is the velocity of light in free-space and β_s is the guided wave number at the grating. Zero reflection and total transmission through the interface are expected at this angle, similar to the Brewster angle condition for a homogeneous dielectric interface. The simple analytical model, used to derive Eq.(2), is based on the TL method. It provides an accurate description of the anomalous funneling mechanism through

the slits, as long as the wavelength $\lambda > d$, ensuring that the impinging energy can funnel into the slits from DC to very high frequencies, up to the wavelength $\lambda_0 = d$.

The free-space input impedance is generally larger than the one inside the slits due to the large value of the ratio d/w . However, it is reduced for oblique incidence and TM polarization and ideal impedance matching is provided when Eq. (2) is satisfied. Note that the presented Brewster angle condition is weakly dependent on frequency and not seriously affected by losses over a broad range of frequencies, as is usually the case for parallel-plate waveguides. Therefore, we have presented the concept of plasmonic Brewster funneling through a metallic grating; a mechanism capable of concentrating the impinging electromagnetic energy over ultra-broad bandwidths inside ultra-narrow channels with zero reflection.

It is very interesting to note that this phenomenon may cover an ultrawide frequency bandwidth. In order to test the bandwidth limitations of the proposed plasmonic Brewster angle concept, we launch ultrashort pulses towards the silver screen shown in Fig. 2 at Brewster angle (computed from Eq. (2) to be $\theta = 74^\circ$ in this case) and at normal incidence ($\theta = 0^\circ$). The frequency and transient time-domain responses are presented in Fig. 3 for both incident angles, and free-space (no metallic screen present) propagation. The transmission coefficient is computed with time domain simulations and it is plotted in Fig. 3(a) versus the frequency of operation. The transmission at Brewster angle is almost perfect for a broad frequency range, spanning 0-350 THz. It accurately follows the response of the wave propagating in free space with no grating present. However, the transmission at normal incidence creates FP resonances and high transmission is achieved only at a narrow range of frequencies.

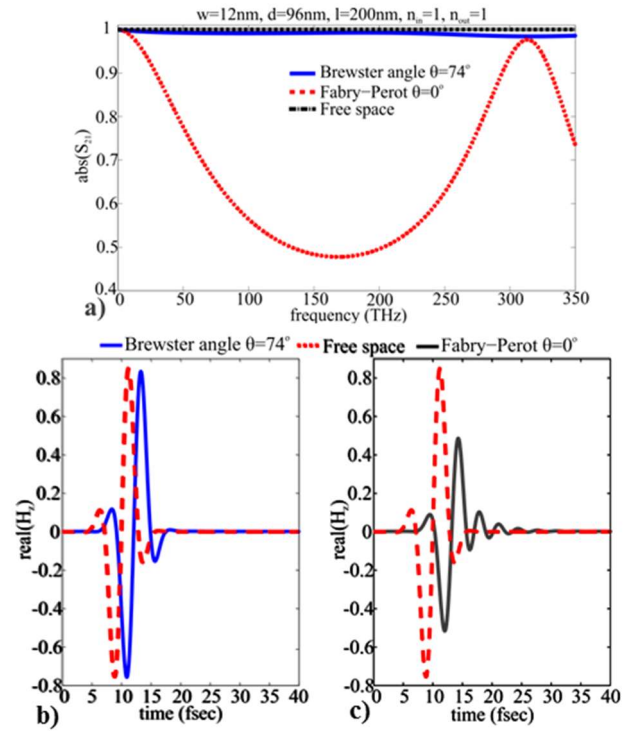


Fig. 3. (a) Transmission as a function of the frequency of illumination for free space (black dashed line), normal incidence (red dotted line) and Brewster angle incidence (blue solid line). (b), (c) The time domain response of the plasmonic grating for Brewster angle incidence (blue line) and normal incidence (black line), respectively. The free space propagating pulse is shown with the dashed red line (From [29]).

Next, the time-domain response of the grating is plotted in Figs. 3(b), (c), when it is excited with an impulse-like short pulse with duration of 10 fs. The obtained results are compared with a case where the pulse propagates in free-space. The real part of the transverse magnetic component of the transmitted pulses at the exit of the sub-wavelength slits is shown in Figs. 3(b), (c) for the Brewster and normal incidence angles, respectively. No distortions are obtained when the ultrashort pulse propagates at the Brewster angle of incidence. This interesting property suggests that ultrashort impinging pulses may be collected, focused and possibly absorbed inside ultrathin gratings, protecting neighboring military components and harvesting the impinging energy. In contrast, the signal is severely distorted and spread in time for normal incidence, as was expected. It should be noted that the signal propagating at the Brewster angle, despite being transmitted without distortion, experiences a time delay compared to the free-space case, similar to ordinary propagation of a pulse through a dielectric slab, characterized by slower propagation.

The ultra-broadband funneling of energy at the Brewster angle may be easily tuned depending on the geometry of the metallic screen, the surrounding material and the material loaded in the grating's channels. This anomalous tunneling phenomenon is able to concentrate all of the impinging energy inside very small apertures, overcoming the severe bandwidth limitations of resonant arrays or apertures commonly used for transmission enhancement and energy concentration. The proposed concept can be generalized and

translated to two-dimensional structures, as illustrated in [30]. If we terminate these 2D gratings with a proper tapering structure and a thick metallic slab [see Fig. 4(a)], the funneled energy will be adiabatically absorbed in the metallic walls by the time it reaches the taper termination. The tapering angle and the corresponding length determine the largest wavelength over which the transmitted energy can get fully absorbed inside the proposed device [51]. The limit in the lowest wavelength of possible absorption is set by the periodicity of the grating placed between the taper and the surrounding free space.

The proposed design for the ultra-broadband absorber is based on combining two inherently broadband effects: the Brewster angle transmission and the adiabatic tapering. The geometry is depicted in Fig. 4(a). An arbitrary TM plane wave impinges on the 2D crossed slit grating, tapered inside a metallic screen to adiabatically enhance the absorption. This is an optimal design for ultra-broadband optical absorption, for which the entrance grating ensures perfect matching to free-space, and the tapering allows absorption over a broad range of frequencies. It can also be further tailored to achieve maximal absorption for a broad set of angles. The plasmonic structure is made of gold (Au) and has dimensions $w = 24\text{nm}$, $d = 96\text{nm}$, $l = 200\text{nm}$, $l_{\text{tap}} = 980\text{nm}$. Free space surrounds the plasmonic device and the dielectric parameters of gold are taken by experimental data [39]. They follow a Drude dispersion model given by:

$$\epsilon = \epsilon_{\infty} - \frac{f_p^2}{f^2 - j\gamma f}, \quad \text{where } f_p = 2069\text{THz} \text{ is the plasma frequency, } \gamma = 17.65\text{THz} \text{ is the collision frequency, and } \epsilon_{\infty} = 1.53 [39].$$

The normalized electric field distribution inside the taper, used in the proposed absorber design, is obtained by full-wave simulations based on the finite-integration method (CST) and it is plotted in Fig. 4(b). It is evident that the fields are gradually dissipated inside the taper and become vanishingly small when they reach the taper's end.

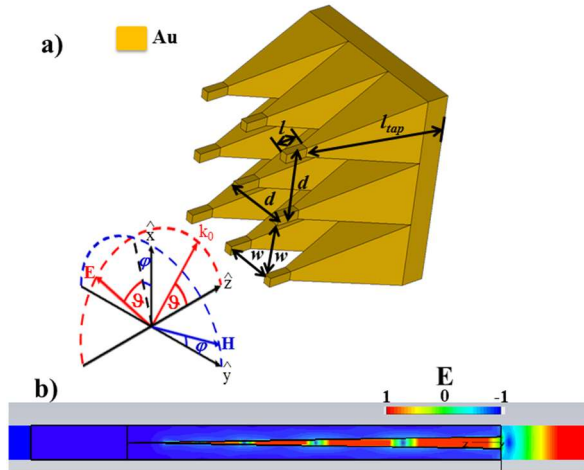


Fig. 4. (a) Geometry of the broadband absorber based on gold Brewster metasurfaces. (From [27]) (b) The normalized electric field distribution inside the plasmonic taper of the proposed broadband absorber.

In Fig. 5, we plot the computed absorption spectrum of the proposed plasmonic system for all incident angles of illumination, which shows very large absorptivity spanning almost the entire THz spectrum, both optical and infrared. The Brewster angle of incidence, where perfect funneling of energy is obtained, is predicted by Eq. (2) to be equal to $\theta_B = 70^\circ$ in this case. As expected, total absorption may be achieved over a very broad range of wavelengths around the Brewster angle. Consistent with the previous discussion, this range may be further broadened, as the upper frequency cut-off (shorter wavelength) is determined by the transverse period, whereas the lower frequency limit is fixed by the taper length. The angle of total absorption is rather flat until we get deep inside the infrared spectrum.

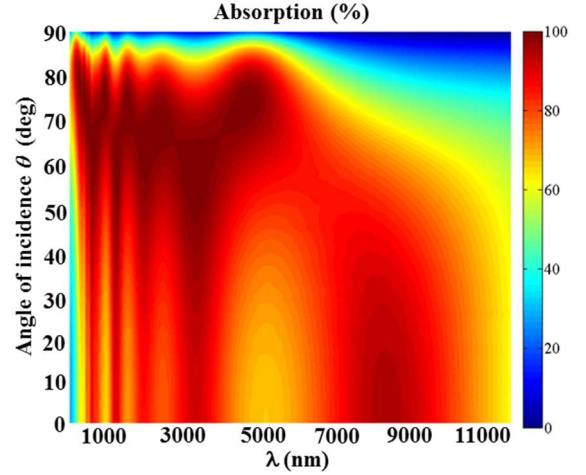


Fig. 5. Calculated absorption of the broadband absorber shown in Fig. 4 as a function of the wavelength and the angle of incidence of the impinging radiation. (From [27])

Large absorption, $A > 70\%$, is achieved for all incident angles in most of the frequency range of the Sun's radiation spectrum, even at normal incidence, except for angles very close to grazing incidence beyond the Brewster angle. Note that the operation of the proposed perfect absorber can be scaled down at lower frequencies, such as microwaves, when we modify its dimensions. The proposed structure forms an omnidirectional and ultra-wideband absorber, which is based on inherently non-resonant mechanisms. Hence, this device can achieve high energy conversion and absorption in the entire solar spectrum and can efficiently capture the solar power and re-use it in different applications, such as in producing electricity. These properties may become of immediate interest for green energy applications.

C. Transformation Electromagnetic Absorbers

Efficient ultra-wideband absorbing and energy concentrating devices can also be designed based on the recent concept of transformation electromagnetics [2]. One example is the perfect metamaterial absorber shown in Figs. 6-7, which mimics the behavior of a celestial black hole. In this case, the impinging radiation beam is concentrated and fully absorbed inside the device's core [33]-[34], [52]. The presented artificial 'black hole' comprises a perfect metamaterial

absorber with cylindrical coating that has inner and outer radii $R_c=3.85\lambda$ and $R_{sh}=13.33\lambda$, respectively, at the design frequency $f=200\text{ THz}$. Here, we present an absorbing device that is directly matched to free space, which is always more desirable for practical applications.

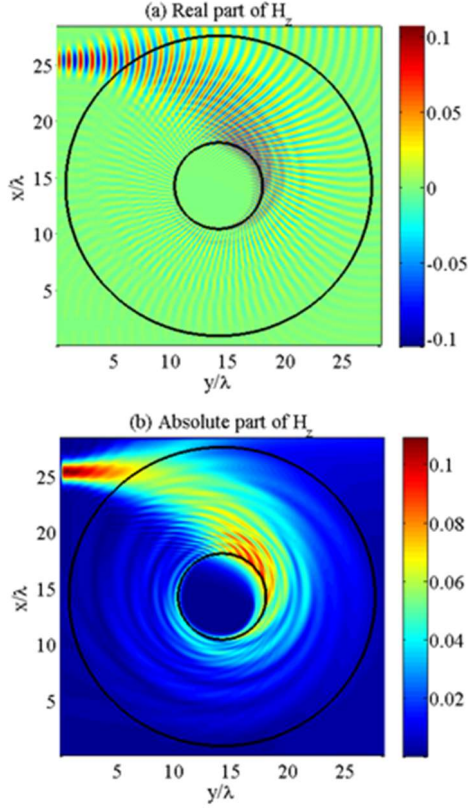


Fig. 6. (a), (b) Real and absolute part of the magnetic field (H_z) distributions for the matched to free-space optical 'black hole'. (From [52])

The presented metamaterial absorber is simulated with the finite-difference time-domain (FDTD) numerical method [52]-[53]. It is composed of conventional dielectric materials and it has an inherent non-dispersive nature. As a result, it can achieve broadband absorption operation. Furthermore, it works for all angles of incident impinging radiation and can have omnidirectional characteristics. It can be constructed with non-resonant metamaterials [54] and it can work for different types of excitation.

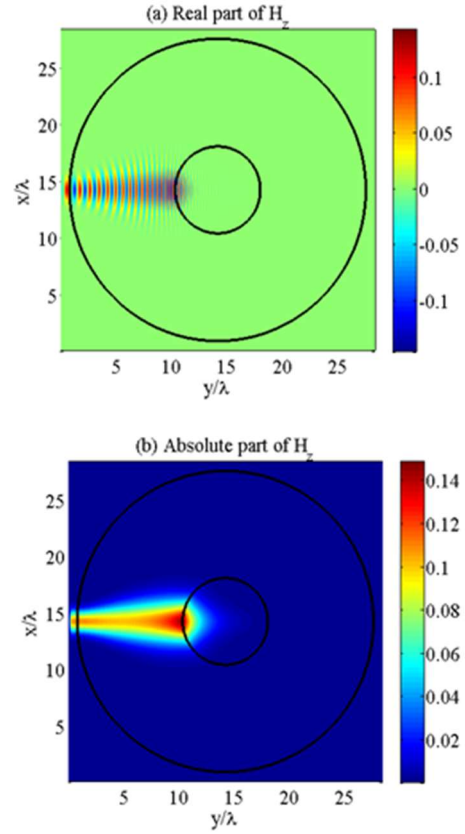


Fig. 7. (a), (b) Real and absolute part of the magnetic field (H_z) distributions for the matched to free-space optical 'black hole'. The pulse is incident with different angle compared to Fig. 6. (From [52])

The radially-dependent permittivity distribution of the cylindrical 2D metamaterial 'black hole' is given by the formula [33]:

$$\epsilon(r) = \begin{cases} \epsilon_0, & r > R_{sh} \\ \epsilon_0 \left(\frac{R_{sh}}{r} \right)^2, & R_c \leq r < R_{sh} \\ \epsilon_c + j\gamma, & r < R_c \end{cases} \quad (3)$$

where ϵ_0 is the permittivity of the surrounding medium (free space), ϵ_c is the permittivity of the core and R_{sh} , R_c are the radii of the shell and core of the device, respectively. The magnetic parameters of the structure are those of free space. The non-magnetic behaviour of the structure is highly desirable, especially at optical frequencies, due to the lack of physical magnetism at this part of the frequency spectrum.

The objective is to design a coating material which is impedance matched to the impedance of the surrounding free space and the core material; and, hence, it reduces the reflection of the impinging electromagnetic waves to a minimum. To achieve this, the radius of the core needs to be calculated based on the parameters of the surrounding medium (free space) and that of the core material. It is given by:

$$\varepsilon(r = R_c) = \varepsilon_c \Leftrightarrow R_c = R_{sh} \sqrt{\frac{\varepsilon_0}{\varepsilon_c}} \quad (4)$$

The core is chosen to be composed of silica with permittivity: $\varepsilon_c + j\gamma = 12 + j0.7$, which is a typical material of a thin film solar cell. The permittivity, given by Eq.(3), takes a finite range of conventional dielectric values $\varepsilon_0 \leq \varepsilon(r) \leq \varepsilon_c$. Hence, the device can be constructed with non-resonant and non-dispersive metamaterials consisting of concentric layers with tunable permittivity with values always higher than the free space permittivity. Note that in contrast to other transformation-based devices (see the rest of absorber designs in this section), in which extreme dispersive parameters enable us to control the waves (such as bending) over sub-wavelength distances, the ‘black hole’ design presented here involves conventional material parameters and require devices that extend several wavelengths in space. This effect introduces challenges in the computational modeling of these devices, since the number of simulation cells increases significantly with the size of the structures. On the other hand, the same effect is expected to make their experimental realization more straightforward [54], since this design requires larger non-resonant metamaterial unit cells that are easier to implement in practice.

Here, we test the absorption performance of the proposed device with FDTD simulations [52]. The spatial resolution is chosen to be uniform and equal to $\Delta x = \Delta y = \lambda/30$, where λ is the wavelength of the excitation signal at free space. The temporal resolution of the 2D FDTD simulation is chosen to be $\Delta t = \Delta x/\sqrt{2}$, in accordance with the Courant stability condition [53], where c is the speed of light in free space. The computational domain is terminated with perfectly matched layers [55]. The 2D FDTD simulations reach the steady-state after approximately 8000 timesteps or 1.5 hours. A temporally infinite, spatially z-polarized Gaussian pulse is used to illuminate the black hole, which is $2\lambda/3$ full-width half-maximum (FWHM) wide in space. Finally, the FDTD domain is noticeably large $28\lambda \times 28\lambda$, because the device operates correctly only when its dimensions are much larger than the wavelength.

The real part and the amplitude of the magnetic field distribution (H_z) are displayed in Figs. 6(a), (b), respectively, when a Gaussian beam impinges on the proposed black hole, and the steady state condition has been reached. The performance of the device is excellent, as it is seen to achieve full absorption of the beam. The absorption performance of the device will be equally perfect, if we illuminate the structure from different angles of incident. This is shown in Fig. 7, where the real part [Fig. 7(a)] and the amplitude [Fig. 7(b)] of the H_z field component are also plotted for a different angle of incidence Gaussian beam excitation. The presented device is indeed an omnidirectional perfect broadband absorber with absorption performance computed to be around 95%, which can be obtained in a broad frequency range. However, it has the disadvantage of larger thickness compared to the other absorbers discussed in this review, which are mainly ultrathin with thicknesses

equal to or less than the wavelength of operation. The metamaterial ‘black hole’ can absorb non-monochromatic pulses and may have several potential applications, ranging from perfect absorbers to state-of-the-art solar cell designs and optoelectronic concentrators.

Another very interesting absorbing device based on transformation electromagnetics can be designed if we manipulate the inherent losses of ideal metamaterial cloaks [31]. Recently, a novel metamaterial device was proposed by Pendry *et al.* [2], the electromagnetic cloak of invisibility. This device is able to guide the electromagnetic waves around an object without any disturbances and reflections, thus making the object placed inside it “invisible”. It can be built with artificially constructed structures, i.e. metamaterials, which allow the full control of the material parameters [3].

Next, we examine several ways to manipulate the loss in electromagnetic cloaks, in order to achieve perfect ultrathin omnidirectional absorbers. The inherent electric and magnetic losses of metamaterials are utilized, as well as additional lossy dielectric materials, and perfect wave absorption is obtained. The proposed new device demonstrates perfect absorptivity over a narrow bandwidth and is suitable for both microwave and optical applications. It manipulates the imaginary part of the complex permittivity and permeability of transformation electromagnetic metamaterials, which characterizes the losses of the structure, and, as it is shown in this review, can also have interesting potential applications, such as the design of more efficient thermal imagers and novel absorbers.

The ideal “cloaking” absorber is simulated with a radially-dependent dispersive FDTD method [56]-[59]. This time-domain numerical technique is advantageous compared to the finite element method (FEM) [60], especially when it is desired to compute the transient response and the operational bandwidth. Transverse magnetic polarized wave source is utilized (E_x , E_y and H_z non-zero field components) to illuminate the two dimensional FDTD modeled lossy cloak, but the perfect cloaking and absorption operation of the device is also present in three-dimensional geometries and for different polarizations of the impinging radiation. The FDTD cell size is $\Delta x = \Delta y = \lambda/150$, where λ is the wavelength of the exciting signal. In this case, we choose the operating frequency to be $f = 2 \text{ GHz}$ and the free space wavelength is $\lambda = 15 \text{ cm}$. However, the operation of the device can be easily scaled up or down to be utilized in different frequencies with some modifications in its geometry. The FDTD computation domain used for the current simulations is shown in Fig. 8(a).

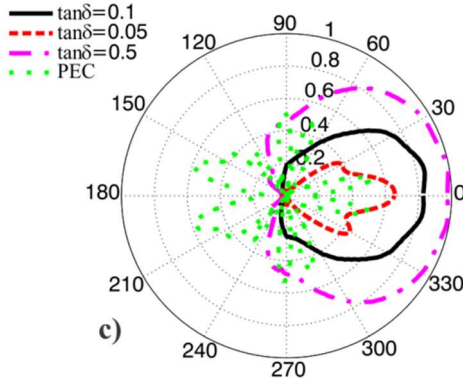
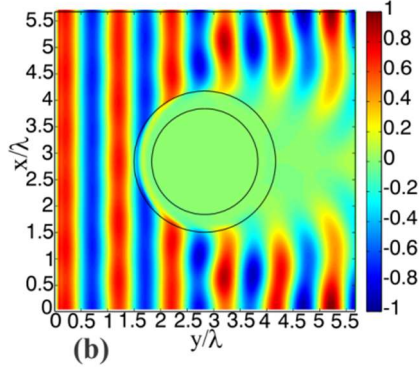
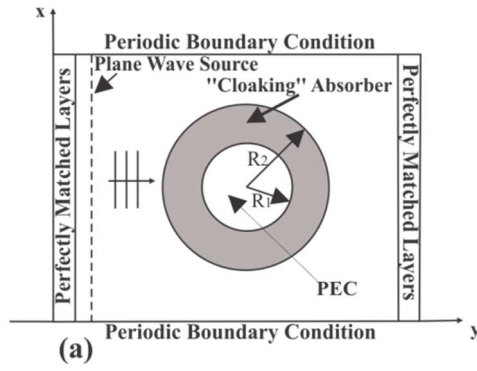


Fig. 8. (a) The FDTD simulation domain of the lossy cloaking structure. (b) The electric field distribution of a plane wave impinging on the proposed absorber device. (c) The scattering distribution of the 'cloaking' absorber when the losses are gradually increased. The scattering pattern of a PEC cylinder is also plotted with the green dotted line. (From [31])

The full set of electromagnetic parameters of the 2D "cloaking" absorber device, in cylindrical coordinates, is given by the following [60]:

$$\epsilon_r(r) = \frac{r - R_1}{r}, \epsilon_\phi(r) = \frac{r}{r - R_1}, \mu_z(r) = \left(\frac{R_2}{R_2 - R_1} \right)^2 \frac{r - R_1}{r}, \quad (5)$$

where the dimensions of the device are $R_1 = \lambda$, $R_2 = 4\lambda/3$, in terms of the wavelength. Hence, the thickness of the absorption coating is only $\lambda/3$, i.e. sub-wavelength thickness. The parameters of the cloaking absorber vary with the radius of the cloak, as is evident from Eq.(5). When the parameters have values $0 \leq \epsilon < 1$ (where ϵ is used throughout the

derivations as an example), they follow a Drude dispersion model:

$$\epsilon = 1 - \frac{\omega_p^2}{\omega^2 - j\omega\gamma}, \quad (6)$$

where ω_p is the plasma frequency and γ is the collision frequency, characterizing the losses of the dispersive material. Furthermore, the parameters in Eq. (5) can also take non-dispersive values ($\epsilon \geq 1$) and follow the dispersion of conventional dielectric/magnetic materials:

$$\epsilon = \epsilon_d + \frac{\sigma}{j\omega} \quad (7)$$

and σ measures the conductive/magnetic losses.

In the case of Drude model dispersion of the material parameters, the lossy parameters can be presented in an alternative way (using ϵ_r as an example here): $\hat{\epsilon}_r = \epsilon_r(1 - j \tan \delta)$, where the radial-dependent parameter ϵ_r is given in Eq. (5) and $\tan \delta$ is the loss tangent of the lossy material. If the previous formula is substituted in the Drude model in Eq. (6) and $\tan \delta$ is assumed constant, the radially-dependent plasma frequency ω_p and collision frequency γ become:

$$\omega_p(r) = \sqrt{(1 - \epsilon_r)\omega^2 + \epsilon_r\omega\gamma \tan \delta} \quad (8)$$

$$\gamma(r) = \frac{\epsilon_r\omega \tan \delta}{(1 - \epsilon_r)} \quad (9)$$

In a similar way, the conductivity σ of the conventional dielectric/magnetic model of Eq. (7) is given by (now using ϵ_ϕ as an example):

$$\sigma(r) = \epsilon_\phi \omega \tan \delta, \quad (10)$$

which is also dependent on the radius of the cloaking absorber, because of the nature of the ϵ_ϕ component [see Eq. (5)]. Hence, the loss is spatially varying in the proposed metamaterial absorber. Note that, the concept of artificial loss functions was also introduced in [61], though for a different transformation electromagnetic function.

The normalized real part of the magnetic field distribution (H_z component) of the FDTD simulated metamaterial absorber, is shown in Fig. 8(b), after the steady-state has been reached for a device with $\tan \delta = 0.5$. It is observed that the backscattering is minimum and the forward scattering (shadow) is maximum –the ideal conditions for a perfectly absorbing body. It is impressive that with such ultrathin subwavelength coating, we are able to achieve almost perfect absorption performance.

In order to better quantify the performance of the proposed absorber, the scattering coefficient σ_s of the device is

calculated with reference to the free space case, with no obstacles present. It is given by the relation:

$$\sigma_s = \frac{\left| \frac{|H_z| - |H_z^f|}{|H_z^f|} \right|}{\left| \frac{|H_z|}{|H_z^f|} \right|}, \quad (11)$$

where H_z is the complex magnetic field distribution recorded on a circular curve surrounding the “cloaking” absorber and H_z^f is the complex magnetic field distribution in the free space, with no obstacles present. When the scattering coefficient σ_s is equal to zero, the surrounding field of the absorber is equal to the free space case, which means that the structure is totally reflectionless ($S_{11}=0$). Moreover, when the scattering coefficient is equal to one, the field is entirely dissipated inside the device ($H_z=0$) and the radiation is not transmitted through the absorber ($S_{21}=0$), which provides an ideal condition for achieving a perfect absorbing structure.

The computed scattering coefficient of the “cloaking” absorber, with a varying loss tangent $\tan\delta$, can be seen in Fig. 8(c), where the scattering of a bare PEC cylinder is also plotted for comparison. It is observed that the backscattering of the “cloaking” absorber, i.e., at an angle equal to 180° in Fig. 8(c), approaches zero for all chosen loss tangents. It is also obvious that in this case that the reflection coefficient approaches zero ($S_{11} \rightarrow 0$). A large shadow is cast at the back of the proposed devices (especially between the angles -30° to 30°), as can be seen in Fig. 8(c), which is the ideal scattering pattern of an efficient absorbing body [62]. The shadow tends to increase with the loss tangent, which is highly desirable in order to achieve an efficient absorbing device. For higher losses ($\tan\delta = 0.5$), it is observed from Fig. 8(c) that the scattering coefficients tend to one (especially at the window -30° to 30°). With a constant loss tangent of 0.1, it has been calculated that the proposed device can achieve an absorptivity of more than $A = 80\%$ within a frequency range of 400 MHz. Furthermore, absorptivity values of $A > 90\%$ can be easily obtained, if the losses are increased.

We also compute the scattering coefficients of the “cloaking” absorber, varying around the operation frequency, chosen here to be $f = 2 \text{ GHz}$, in order to test the bandwidth limitations of this transformation based device. The results can be seen in Fig. 9, where the scattering coefficients of the structure at frequencies above and below the central operation frequency of $f = 2 \text{ GHz}$ are plotted in Figs. 9(a) and 9(b), respectively. The lowest backscattering is obtained at the design frequency of $f = 2 \text{ GHz}$. Unfortunately, the values of the backscattering are found to increase at other frequencies due to the dispersive nature of the cloak. However, we can still claim that the proposed device can have a decent absorption for a reasonable bandwidth, which makes it well suited for moderate bandwidth absorption applications, i.e., reducing the radar cross section (RCS) of an object within a particular frequency window. This device can also operate correctly at every angle of incidence in a fixed surface, due to its cylindrical geometry. It can be concluded that it is another alternative design of a perfect metamaterial absorber. Finally, we would like to mention

that alternative, but much more narrowband transformation based techniques exist to increase the absorption efficiency, such as by surrounding a lossy material with a negative refractive index shield [63].

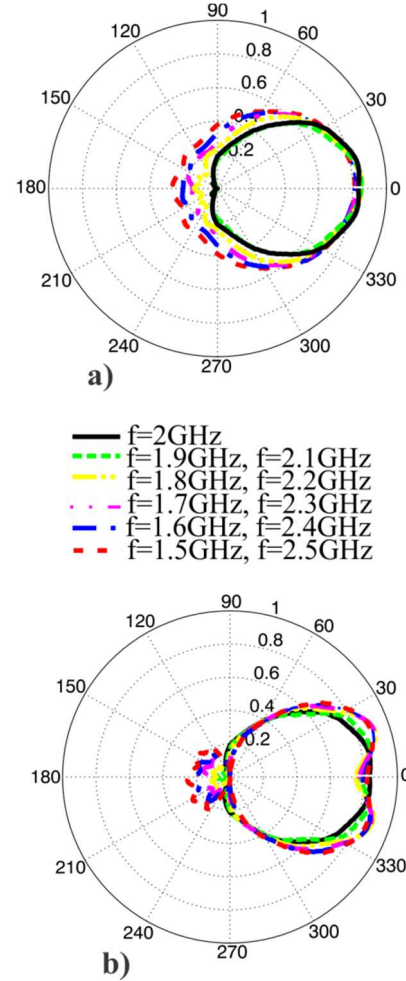


Fig. 9. (a) The scattering distribution of the lossy ($\tan\delta = 0.1$) ‘cloaking’ absorber at frequencies above the central cloaking frequency ($f = 2 \text{ GHz}$). (b) The scattering distribution of the lossy ($\tan\delta = 0.1$) ‘cloaking’ absorber at frequencies below the central cloaking frequency ($f = 2 \text{ GHz}$).

The loss tangent values of the “cloaking” absorber and, in general, the losses of all the proposed absorbers in this review can be controlled with different practical techniques, depending on the desired frequency of operation. Different substrate dielectric materials can be chosen at the microwave frequency regime, where the dielectric losses are dominant [64]. Alternatively, metal nanowires can be introduced into the substrate, which can lead to a loss tangent on the order of 0.1 [65]. Another approach is to introduce lattice defects by doping the crystalline structure of the dielectric substrate [66]. At higher frequencies, such as infrared and optics, the ohmic losses are more significant [64], which leads to the solution of changing the metallic material of the resonator particles (for example, gold is more lossy than silver at infrared frequencies). In addition, the loss tangent can be enhanced by increasing the density of the metamaterial

elements, by simultaneously reducing their electrical dimensions [67].

Finally, the cylindrical concentrator is another interesting metamaterial device which is also reflectionless and can concentrate the electromagnetic power by squeezing the external incident fields inside its core [32]. It is also derived from transformation electromagnetics and can be designed with metamaterials. Novel energy concentrators can be used in conjunction to solar cell designs in order to achieve more efficient production of electric power from the Sun's radiation. These concentrators can be designed based on the presented exotic device. The geometry of the concentrator is shown in Fig. 10(a), where R_1 is the radius of the core, R_2 the radius of the inner cylinder, R_3 the radius of the outer cylinder and r an arbitrary radius inside the device.

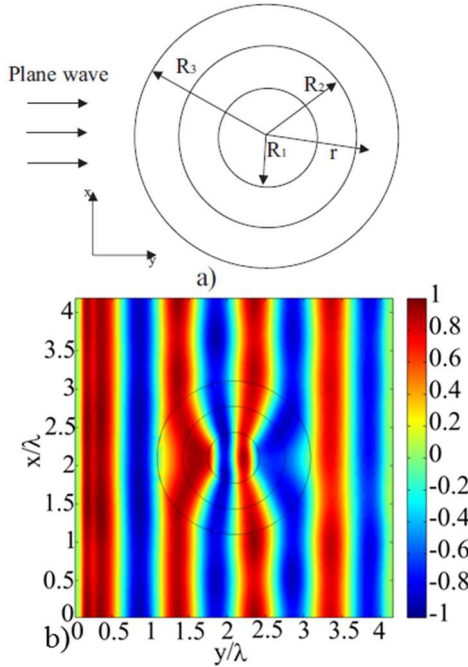


Fig. 10. (a) The geometry of the ideal concentrator. (b) The magnetic field (H_z) distribution of the ideal concentrator based on transformation electromagnetics.

The device is again modeled with the FDTD method to simulate the lossy ‘cloaking’ absorber [56]-[58]. The material parameters for the TM polarized incidence are ϵ_r , ϵ_ϕ , μ_z in cylindrical coordinates, and three field components, namely E_x , E_y and H_z exist in this 2D simulation. An extra fine and uniform spatial discretization is used, with an FDTD cell size of $\Delta x = \Delta y = \lambda/150$, where λ is the wavelength of the exciting signal. This fine mesh is employed to safeguard against potential numerical instabilities involved in the simulation of this complicated structure. The operating frequency is chosen to be $f = 2 \text{ GHz}$; so, the free space wavelength is $\lambda = 15 \text{ cm}$, although the structure can be scaled to higher frequencies just by decreasing its geometrical size. The temporal discretization is always chosen in accordance with the well-known Courant stability condition [53] with a time step given by

$\Delta t = \Delta x / \sqrt{2}$, where c is the speed of light in free space. The permittivity and permeability values outside the core ($R_1 < r \leq R_3$) and inside the core ($r \leq R_1$) are given by the following formulas that have been provided in [32]. For $R_1 < r \leq R_3$:

$$\begin{aligned} \epsilon_r &= \frac{R_2 - R_1}{R_3 - R_2} \cdot \frac{R_3}{r} + 1, \\ \epsilon_\phi &= \frac{1}{\epsilon_r}, \\ \mu_z &= \left(\frac{R_3 - R_2}{R_3 - R_1} \right)^2 \cdot \left(\frac{R_2 - R_1}{R_3 - R_2} \cdot \frac{R_3}{r} + 1 \right). \end{aligned} \quad (12)$$

In the inner core, $r \leq R_1$, we have:

$$\epsilon_r = 1, \epsilon_\phi = 1, \mu_z = \left(\frac{R_2}{R_1} \right)^2. \quad (13)$$

The concentrator has dimensions $R_1 = 2 \text{ cm}$, $R_2 = 4 \text{ cm}$ and $R_3 = 6 \text{ cm}$ and it operates at the frequency of $f = 2 \text{ GHz}$. The electric and magnetic parameters can take dispersive values $\epsilon, \mu < 1$ and this leads to narrowband concentration operation. The computed magnetic field distribution (H_z) is plotted in Fig. 10(b). It is obvious that the impinging radiation is squeezed and concentrated inside the core of the device. The power inside the core of the device is enhanced by a factor equal to R_2/R_1 [32]. As a result, the concentrator is an ideal candidate to be employed in solar cells or in similar devices to improve their efficiency. Finally, note that the practical implementation of all the presented transformation-electromagnetic-based devices may become simpler, if we employ more relaxed conformal transformations to obtain their design. This can lead to much simpler permittivity and permeability distributions without anisotropic or dispersive values [68]-[69].

IV. CONCLUSIONS

In summary, different metamaterial and plasmonic absorber designs have been presented in this paper. Flexibility in tailoring the wave interaction provided by metamaterials and metasurfaces has been employed, not only to suppress the scattering or to divert impinging waves, but also to concentrate, absorb and focus their energy. In this review, the devices that were presented exhibit narrow and broad bandwidth responses depending on the different physical mechanisms involved in their operation. The ability to manipulate and control the absorption spectrum in different ways may pave the way to new absorption devices with a wide range of multidisciplinary applications, including biological sensors, military, renewable energy and communications. In addition, the concept of plasmonic Brewster angle transmission was examined, which may allow ultra-wideband energy localization and absorption in

sub-wavelength metallic channels. We envision that these metamaterial and plasmonic absorber designs can lead to robust and efficient narrowband and broadband designs of novel photovoltaic structures, bolometers, solar filters, new energy harvesting devices and solar energy concentrators. Furthermore, new thermal emitters can be designed, which selectively guide and focus the thermally emitted radiation to single-junction or multi-junction solar cells. Finally, note that the proposed devices can also be designed to operate with other types of waves instead of electromagnetics, in particular blast, mechanical, acoustic and matter waves.

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